HISTORY OF MILKY WAY DWARF SPHEROIDAL GALAXIES IMPRINTED ON ABUNDANCE PATTERNS OF NEUTRON-CAPTURE ELEMENTS

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Abstract

Stellar abundance pattern of n-capture elements such as barium is used as a powerful tool to infer how star formation proceeded in dwarf spheroidal (dSph) galaxies. It is found that the abundance correlation of barium with iron in stars belonging to dSph galaxies orbiting the Milky Way, i.e., Draco, Sextans, and Ursa Minor have a feature similar to the barium-iron correlation in Galactic metal-poor stars. The common feature of these two correlations can be realized by our inhomogeneous chemical evolution model based on the supernova-driven star formation scenario if dSph stars formed from gas with a velocity dispersion of ~ 26 km s^{-1}. This velocity dispersion together with the stellar luminosities strongly suggest that dark matter dominated dSph galaxies. The tidal force of the Milky Way links this velocity dispersion with the currently observed value $\lesssim 10$ km s^{-1} by stripping the dark matter in dSph galaxies. As a result, the total mass of each dSph galaxy is found to have been originally ~ 25 times larger than at present. Our inhomogeneous chemical evolution model succeeds in reproducing the stellar [Fe/H] distribution function observed in Sextans. In this model, supernovae immediately after the end of the star formation epoch can expel the remaining gas over the gravitational potential of the dSph galaxy.

Key words: galaxies: abundances — galaxies: evolution — stars: abundances — galaxies: individual (Draco, Sextans, Ursa Minor) — supernovae: general — supernova remnants

1. INTRODUCTION

There is no room for doubt that the recent progress on abundance determination for numerous solar neighborhood stars promotes a better understanding of the nature of the Milky Way because stellar abundance patterns bring us valuable information on how the Milky Way formed and has evolved (Wheeler, Sneden, & Truran 1989; McWilliam 1997). We have now reached the stage where we can learn the history of other nearby galaxies from detailed elemental abundances of individual stars.

Recently Shetrone, Côté, & Sargent (2001), hereafter SCS01 revealed the abundance patterns for red giant stars belonging to three Galactic dwarf spheroidal (dSph) galaxies, i.e., Draco, Sextans, and Ursa Minor. These three galaxies share similar features and reside in a similar environment (e.g., Mateo 1998). Some important properties are shown in Table 1. Remarkable features in the abundance patterns of these dSph stars are found in neutron-capture elements such as barium (Ba) and europium (Eu) (SCS01): first, the observed Ba/Eu ratios are very close to the pure r-process ratio; second, there exist stars having very high r-process element abundances with respect to iron (Fe). These features are shared with extremely metal-poor halo stars in the Milky Way (McWilliam et al. 1995; McWilliam 1998).

Needless to say that the first feature suggests that Ba in these dSph stars is of r-process origin. In addition, the Ba/Eu ratio is expected to work as a *cosmic clock* which tells us the stellar age – that is – the timescale for the formation of dSph galaxies. In general, the Ba/Eu ratios in stars increases with time because the s-process synthesizes Ba but little Eu and it takes a much longer time for the s-process to contribute to the chemical enrichment than the r-process (e.g., Pagel 1997). It comes down to that the pure r-process Ba/Eu ratio in stars indicates that these stars had been formed before the s-process began to produce Ba. As a result, the timescale of the star formation in these dSph galaxies needs to be less than a few 10^8 years. This short timescale strongly suggests that there must be no contribution to the chemical evolution from type Ia supernovae (SNe Ia). Thus the small Mg/Fe ratios observed in dSph stars might be ascribed to the rapid p-capture process that converts Mg into aluminum (Al) with the help of deep mixing in stars (Sweigart & Mengel 1979; Fujimoto, Aikawa, & Kato 1999), though the abundances of Al in dSph stars were too poorly estimated to tell if this process occurs in dSph stars (SCS01).

Table 1. Observed Properties of Three Galactic Dwarf Spheroidal Galaxies

Galaxy	<[Fe/H]>[a] dex	σ_*[b] (km/s)	L_V[c] ($L_\odot$)	Distance[d] (kpc)	Core Radius r_c (arcmin)	Tidal Radius R_t (arcmin)
Draco	-2.0 ± 0.15	9.5±1.5	$(1.8 \pm 0.8) \times 10^5$	71 ± 7[e]	$8'.7 \pm 0'.3$[e]	$49'.4 \pm 1'.4$[e]
Ursa Minor	-2.2 ± 0.1	9.3±1.6	$(2.0 \pm 0.9) \times 10^5$	69 ± 4[f]	$15'.8 \pm 1'.2$	$50'.6 \pm 3'.6$
Sextans	-2.1 ± 0.04[g]	6.6±0.7	$(4.1 \pm 1.9) \times 10^5$	86 ± 4	$16'.6 \pm 1'.2$	$160' \pm 50'$

Note.– All data for which references are not indicated are from Mateo (1998). [a]Mean iron stellar abundance. [b]Stellar central velocity dispersion. [c]Visual Luminosity, from Irwin & Hatzdimitriou (1995). [d]Distance from the center of the Milky Way. [e]From Suntzeff et al. (1993). [f]From Odenkirchen et al. (2001). [g]From Eskridge & Schweitzer (2001).

To avoid the influence by nuclear reactions that might occur inside old stars, we will extract information on history of dSph galaxies from the abundances of elements heavier than Fe.

The second feature is very intriguing. Elements such as Ce, Nd, and Sm as well as Eu and Ba are enhanced with respect to Fe in some dSph stars, as shown in Figures 3 and 4 in SCS01, which reminds us of notable neutron-capture-rich giant stars – CS22892-052 and CS31082-001 – (Sneden et al. 2000; Hill et al. 2001) in the Galactic halo. Table 2 clarifies the similarity in the [*r*-process/Fe] ratios of CS22892-052 and two dSph stars. Furthermore, the correlations of [Ba/Fe] ratios with [Fe/H] in these two types of stars are found to be quite similar if the metallicities [Fe/H] of dSph stars are shifted by the amount Δ[Fe/H] $= -0.6$ dex. Figure 1 shows the correlation of [Ba/Fe] with [Fe/H] for dSph stars (SCS01), together with that for Galactic metal-poor stars (*crosses*; McWilliam 1998). Filled circles represent dSph stars with [Fe/H] shifted by Δ[Fe/H] $= -0.6$ dex. An excellent coincidence between two distributions appears: both metal-poor stars and dSph stars populate two separate branches in the [Ba/Fe]-[Fe/H] plane, i.e., the first branch in which stars have positive [Ba/Fe] ratios (i.e., greater than the solar ratio), and the second branch with the upper bound at [Ba/Fe]$=-1$. Though such a coincidence can be also obtained with -0.8 dex$\leq\Delta$[Fe/H]≤-0.6 dex, we prefer Δ[Fe/H]$=-0.6$ dex that will be justified in §4.

Tsujimoto, Shigeyama, & Yoshii (2000) associate this feature, a bifurcation of the observed element ratios [Ba/Fe], with two distinct SN classes: one that synthesizes and ejects *r*-process elements and the other that does not (Tsujimoto et al. 2000; Tsujimoto & Shigeyama 2001), based on their inhomogeneous chemical evolution model in which stars are born from the matter swept up by individual supernova remnants (SNRs). This assumption is essential to understand the observed elemental abundance pattern in halo field stars and the chemical evolution at the early epochs of the Milky Way (Shigeyama & Tsujimoto 1998; Tsujimoto & Shigeyama 1998, Tsujimoto, Shigeyama, & Yoshii 1999, 2000, 2002). The common feature in the abundance patterns of Galactic metal-poor stars and dSph stars strongly suggests that this mechanism also works in dSph galaxies.

DSph galaxies have little gas, extremely low surface brightness, and low metallicities. These features have been ascribed to gas removal by SN explosions from a galaxy embedded in dark halo (Dekel & Silk 1986). Their scenario apparently reproduces some observed relations for dSph galaxies. However the tidal force from the Milky Way must affect the dynamics of these galaxies, which Dekel & Silk (1986) ignored. Such environmental effects are indeed imprinted on the elemental abundance patterns observed for dSph stars (see the next section).

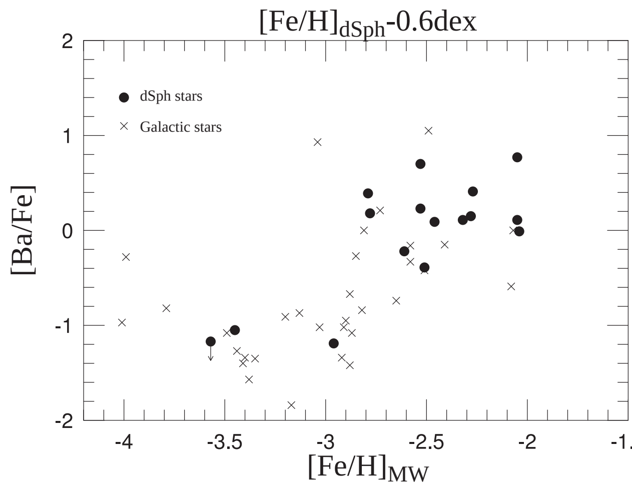

Fig. 1. Correlations of [Ba/Fe] with [Fe/H] for dSph stars (*filled circles*; SCS01) and Galactic halo field stars (*crosses*; McWilliam 1998). The data of dSph stars are shifted by the amount of Δ[Fe/H]=–0.6 dex (see the text). The K star of Ursa Minor is excluded from the plots because it is recognized to be a carbon star, most probably self-enriched by *s*- process material.

In this *letter*, we describe the star formation history of a dSph galaxy in terms of an inhomogeneous chemical evolution model developed for the halo of the Milky Way. The observed abundance trends seen in neutron-capture elements and stellar abundance distribution function (ADF) constrain our model to shed light on the history of dSph galaxies and the environmental effects on these galaxies.

2. HISTORY OF GALAXIES IMPRINTED ON STARS

The metallicities of metal-poor stars are determined by two factors: how much heavy-element mass an SN supplies and how much interstellar matter (ISM) mass was eventually swept by a single SN explosion (Shigeyama & Tsujimoto 1998). The former is determined exclusively by

Table 2. Comparison of Elemental Abundances between CS22892-052 and Dwarf Spheroidal Stars

Star	Galaxy	[Fe/H]	[Ba/Fe]	[Ce/Fe]	[Nd/Fe]	[Sm/Fe]	[Eu/Fe]	[Ba/Eu]
CS22892-052	the Milky Way	−3.10	0.91	1.05	1.22	1.56	1.66	−0.75
199	Ursa Minor	−1.45	0.77	1.03	1.13	1.75	1.49	−0.72
S35	Sextans	−1.93	0.70	0.89	0.79	1.58	–	–

Note.– The star K in Ursa Minor is much more enhanced in [X/Fe] than above dSph stars. However the Ba/Eu ratio in this star is far deviated from the value anticipated from the pure r-process origin.

each SN. On the other hand, the latter quantity is influenced by the environment such as the velocity dispersion $\sigma_{\rm v}$ and density n of the ISM. If SNe in the Milky Way and those in dSph galaxies are similar, different environments should give rise to the Δ [Fe/H] discussed above. Since the mass $M_{\rm sw}$ swept up by an SN is much more sensitive to the velocity dispersion than to the density; $M_{\rm sw} \propto \sigma_{\rm v}^{-9/7} n^{-0.062}$ (Shigeyama & Tsujimoto 1998), it is likely that a larger velocity dispersion in dSph galaxies at the star formation epoch enhanced the stellar [Fe/H]. Quantitatively, Δ [Fe/H]=–0.6 dex corresponds to a velocity dispersion of $\sigma_{\rm v} \sim 26$ km s^{-1}. The velocity dispersion $\sigma_\star$ of stars at the star formation epoch must have a similar value in equilibrium configuration. The present value of $\sigma_\star$ measured in Galactic dSph galaxies are about 9 km s^{-1} (see Table 1). These two significantly different velocity dispersions can be connected in the context of a galaxy losing mass by the tidal force of the Milky Way. The tidal radius $R_{\rm t}$ of a dSph galaxy with a mass of $M_{\rm dSph}$ at a distance of D from the center of the Milky Way can be expressed as,

$$R_{\rm t} \sim D \left(\frac{M_{\rm dSph}}{2M_{\rm MW}}\right)^{\frac{1}{3}},$$

$$\sim 1\,{\rm kpc} \left(\frac{M_{\rm dSph}}{2\times 10^7\,M_\odot}\right)^{\frac{1}{3}} \left(\frac{D}{70\,{\rm kpc}}\right). \qquad (1)$$

Here the mass of the Milky Way is denoted by $M_{\rm MW}$ and assumed to be $3\times 10^{12}\,M_\odot$ (Klessen & Kroupa 1998). Since the actual sizes of dSph galaxies are also $\sim$1 kpc, dSph galaxies are likely to be affected by the tidal force of the Milky Way. If a dSph galaxy extends to the tidal radius and in virial equilibrium, the velocity dispersion is given by

$$\sigma_\star \sim \sqrt{\frac{GM_{\rm dSph}}{R_{\rm t}}} = \sqrt{\frac{GM_{\rm MW}}{D}} \left(\frac{\sqrt{2}M_{\rm dSph}}{M_{\rm MW}}\right)^{\frac{1}{3}},$$

$$\sim 9\,{\rm km\,s^{-1}} \left(\frac{M_{\rm dSph}}{2\times 10^7\,M_\odot}\right)^{\frac{1}{3}} \left(\frac{D}{70\,{\rm kpc}}\right)^{-\frac{1}{2}}. \qquad (2)$$

The above formulae well describe results of numerical N-body calculations for Galactic dSph galaxies (Oh, Lin, & Aarseth 1995). A larger velocity dispersion at the star formation epoch inferred from the elemental abundance pattern suggests that the total mass of the dSph galaxy at that time must be $\sim$25 times larger than at present (see Eq. (2)). The timescale $|dt/d\ln M_{\rm dSph}|$ for stripping is expressed and evaluated as $|dt/d\ln M_{\rm dSph}| = 2\sqrt{3}R_{\rm t}/\sigma_\star = \sqrt{12D^3/(GM_{\rm MW})} \sim 1.5-3\,{\rm Gyr}$, depending on the estimated mass of the Milky Way. From this timescale and the initial mass of the dSph galaxy, the corresponding age of Galactic dSph galaxies is estimated to range from 5 to 10 Gyr.

From an elemental abundance pattern which has been converted to information on the velocity dispersion of gas, we have estimated the initial dynamical (total) mass of dSph galaxies. In the same manner, i.e., from the chemical properties imprinted on stars, we deduce the baryonic mass initially residing in dSph galaxies. From the conservation of Fe, we have the relation $Z_s M_s + Z_g M_g = y M_s$, where M_s: the mass of stars, Z_s: the mean metallicity of stars, $M_g(Z_g)$: the mass (metallicity) of the gas at the end of star formation, and y: the Fe yield (see Tinsley 1980). If we define $\varepsilon_{\rm s}$ as the mass fraction of the initial gas that has been converted to stars in the end, then $\varepsilon_{\rm s}$ can be expressed as $\varepsilon_{\rm s} = Z_g/(y+Z_g-Z_s)$. From the ADF for Sextans observed by Suntzeff et al. (1993) (see Fig. 2), we have [Fe/H]=−2.0 for Z_s, and [Fe/H]=−1.6 (corresponding to the metallicity of the most metal-rich star) for Z_g. Adopting y=0.38$Z_{{\rm Fe},\odot}$ for the Fe yield from SNe II (Tsujimoto et al. 1997), we deduce $\varepsilon_{\rm s} \sim 0.05$. Our numerical calculation presented in the next section confirms this value. Thus the initial gas (baryonic) mass was 20 times larger than the present stellar mass. Interestingly the ratio of the initial to the present baryonic mass is close to that for dark matter. In other words, the baryonic fraction $f_{\rm b}$ in a dSph galaxy is quite similar at these two phases.

We try to make a rough estimate of $f_{\rm b}$ for Draco. Taking $L_{\rm V} = 1.8\times 10^5 L_{{\rm V},\odot}$ (Irwin & Hatzdimitriou 1995) and the mass-to-light ratio for old stellar populations $M_\star/L \sim 8$ (van der Marel 1991), we obtain the present baryonic mass $\sim 1.4\times 10^6 M_\odot$. If we adopt the present dynamical mass of $2.2\times 10^7 M_\odot$ (Odenkirchen et al. 2001), we obtain $f_{\rm b} \sim 0.06$. Our scenario predicts that $f_{\rm b}$ was also ~ 0.06 at the initial formation phase.

In our inhomogeneous chemical evolution model, the star formation is terminated when too many SNe explode to sweep a sufficient amount of the ISM. The number of these SNe is found to be a few hundred from our model. These last few hundred SN explosions were able to disperse the remaining gas over the potential well made by dark matter (see discussion in §4).

3. INHOMOGENEOUS CHEMICAL EVOLUTION

In this section we discuss Ba and Fe in dSph galaxies in terms of the inhomogeneous chemical evolution model presented in Tsujimoto et al. (1999). The model is based on a scenario where the chemical evolution proceeds through a repetition of a sequence of SN explosion, shell formation, and star formation in the matter individual SNRs sweep up. As discussed in the previous section, the velocity dispersion of gas is assumed to be a constant value 26 km s^{-1} because the timescale of tidal interaction is $\sim$10 times longer than that of star formation. The free parameters in our model are the mass fraction $x_{\rm III}$ of metal-free stars initially formed, and the mass fraction ϵ of stars formed in the dense shells swept up by each SNR. We simply take $x_{\rm III} = 2.5 \times 10^{-4}$ inferred from the Ba abundances of extremely metal-poor stars in the Milky Way (Tsujimoto et al. 2000), because the results are rather insensitive to this value. Stars are assumed to be formed following the Salpeter initial mass function.

The value of ϵ is determined in order to reproduce the observed ADF (Tsujimoto et al. 1999). The location of the ADF peak is sensitive to what fraction of the gas has been converted into stars in the end. The observed peak for Sextans at [Fe/H] ~ -2 (Suntzeff et al. 1993) requires less efficient star formation than in the Galactic halo the ADF of which has a peak at [Fe/H] ~ -1.6. A conversion of $\sim$5 % of the gas into stars is found to give the best fit to the observed ADF, which is realized by $\epsilon = 1.5 \times 10^{-2}$. This ϵ produces slightly more than one star that can explode as a SN per SNR shell on average. Figure 2a shows the ADF obtained by our model, as compared with the data acquired by Suntzeff et al. (1993). The result has been convolved with a Gaussian with the dispersion of σ=0.1 dex which is identical to the measurement error in [Fe/H]. A good agreement with the data is obtained, though the number of the observed stars is too small to strictly constrain models.

Assuming that SNe II with $M_{\rm ms} = 20 - 25 M_\odot$ are the dominant site for r-process nucleosynthesis (Tsujimoto et al. 2000; Tsujimoto & Shigeyama 2001), we calculate the Ba evolution in dSph galaxies. Figure 2b is a color-coded predicted frequency distribution of stars in the [Ba/Fe]-[Fe/H] plane, normalized to unity when integrated over the entire area. In order to make a direct comparison with the data, the frequency distribution has been convolved with a Gaussian with σ= 0.2 dex for [Ba/Fe] and σ=0.1 dex for [Fe/H]. Our model predicts a bent arrow-like frequency distribution of stars, which covers the present observational data points.

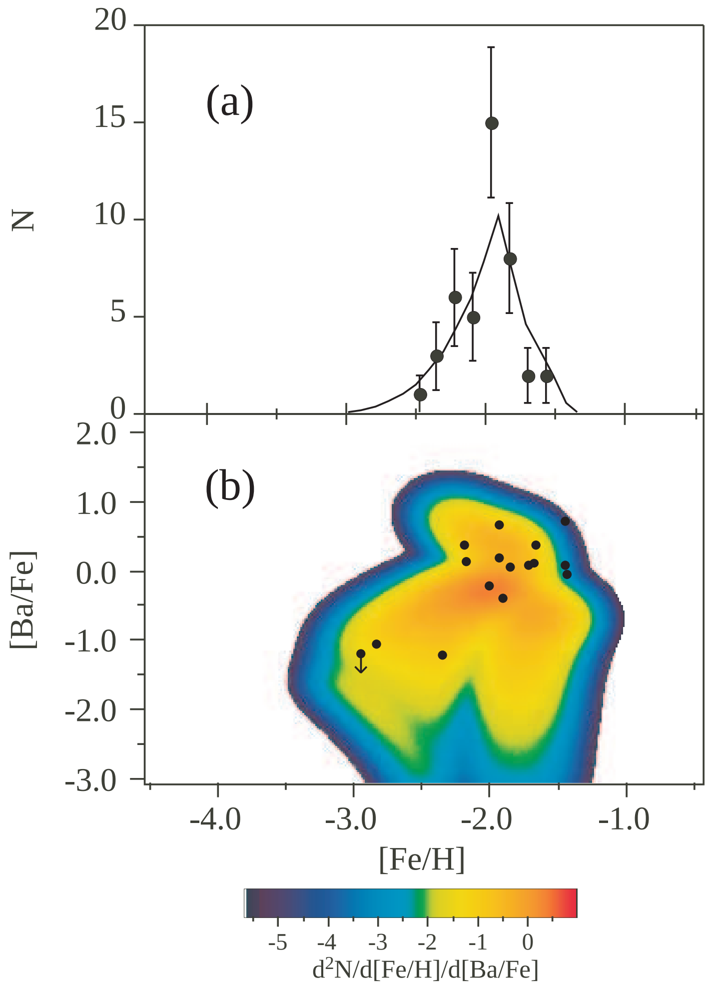

Fig. 2. (a) The frequency distribution of dSph stars against the iron abundance, compared with the observation for Sextans (Suntzeff et al. 1993). The error bars take into account Poisson noise. (b) The color-coded frequency distribution of dSph stars in the [Ba/Fe]-[Fe/H] plane convolved with a Gaussian having $\sigma = 0.2$ dex for [Ba/Fe] and $\sigma = 0.1$ dex for [Fe/H]. Filled circles show the data of SCS01.

4. GAS REMOVAL

In our model, the formation of new stars is terminated when SNRs sweep up too little gas without being affected by other SNe to form cool shells. After the end of star formation, the remaining gas is therefore heated up by SN explosions without experiencing effective radiative cooling. The total energy added by these last SNe amounts to $\sim 5 \times 10^{53}$ erg. As compared with the gravitational binding energy of the remaining gas $E_{\rm g} \sim GM_{\rm dSph}M_{\rm gas}/R_{\rm t} \sim 4 \times 10^{53}$ erg, all the gas could be expelled by these SNe. If the energy supplied by the last SNe were significantly smaller than $E_{\rm g}$, the gas would still remain in the gravitational potential. Then the star formation would recommence in the radiative cooling timescale. Such a situation would be realized if the metallicity difference between dSph stars and Galactic field stars was Δ[Fe/H]$\approx -0.7 - -0.8$dex. In this case, a larger velocity dispersion of gas in the proto-dSph galaxies would result in $E_{\rm g} \gtrsim 10^{54}$ erg. No sign of the second episode of star formation in neither the observed ADF nor Ba/Eu ratios suggests that this is not the case.

The total number of SNe is $\sim$3,000 throughout the star formation episode in our model. If all the explosion energy

of these SNe were converted into kinetic energy of the gas, the mean velocity would become 100 km s^{-1} at most. Thus it is likely that our model dSph galaxy never satisfies the criterion for SN-driven winds proposed by Dekel & Silk (1986) that SNe increase the velocity dispersion of the gas to greater than $\sim$100 km s^{-1} to escape from a dSph galaxy. Therefore more SNe are needed to expel the gas by SN-driven winds according to Dekel & Silk (1986). In other words, a galaxy that satisfied this criterion would produce too much heavy-element mass to reconcile with the mean stellar Fe abundances in Table 1.

5. CONCLUSIONS AND DISCUSSIONS

We show that stellar elemental abundance patterns for n-capture elements have shed light on the histories of galaxies. The Ba/Eu ratios in dSph stars severely constrain the timescale of the star formation to be of the order of 10^8 yr. Recently observed correlation of [Ba/Fe] with [Fe/H] for dSph stars can be reconciled with that seen in Galactic halo stars by introducing a larger velocity dispersion in dSph galaxies at the star formation epoch, if stars are born from individual SNRs. These considerations lead us to our finding that dSph stars were born from the gas with its velocity dispersion of ~ 26 km s^{-1}, which results in a mass of the proto-dSph galaxies $\sim$25 times larger than at present. The path to the present dSph galaxies is likely to be controlled by the tidal interaction with the Milky Way.

The history of Galactic dSph galaxies that we have proposed is as follows. The proto-dSph galaxy consisted of gas and dark matter, and was approximately 25 times as massive as a present dSph galaxy. Star formation lasted for about 2×10^8yr; meanwhile, ~ 5 percent of the gas converted into stars. Afterward, the remaining gas was dispelled by the last SN explosions. On the other hand, dark matter which surrounds stars has lost more than 90% of its mass through the tidal interaction with the Milky Way.

Lighter elements might include information that has not been discussed in this paper. Deficiencies in Ca/Fe and Ti/Fe ratios are also seen in dSph stars (SCS01) as compared to the halo stars, though not so pronounced as Mg/Fe. In the framework of our inhomogeneous chemical evolution model, these deficiencies should be attributed to SNe II in dSph galaxies that yield a relatively small amount of α elements as compared with Fe and/or SNe that yield a large amount of Fe. The former SNe will not alter our scenario for dSph galaxy evolution. In the latter case, the SNe yields will contribute to a part of the discrepancy in Fe/H ratios between the Milky Way and dSph galaxies and reduce the initial velocity dispersion (and mass) of matter accordingly.

Further stellar abundance measurements not only for dSph galaxies discussed here but also for other nearby galaxies promise an understanding of their star formation histories more precisely than deciphering the color-magnitude diagram of evolved stars which has been employed so far.

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